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A Vibrating String Experiment

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Abstract
A simple experiment demonstrating the excitation of a standing wave in a metal string is presented here. Several tasks using the set-up are considered, which help the students to better understand the standing waves, the interaction between electric current and magnetic field and the resonance phenomena. This can serve also as a good lecture demonstration for high school and undergraduate students.
Keywords: standing waves, resonance phenomena, classroom experiment

Introduction

Standing wave demonstrations take place in many classroom experiments. Different mechanisms are used to excite such a wave. Some of them use a coil extension spring suspended between two light supporting wires to demonstrate a string with free ends (Kashy *et al.*, 1997) or just pluck a stretched string (Gluck, 2009). Another option is to connect an inelastic string to one of the prongs of a tuning fork, which is droved by an excited coil placed between the prongs (Chen, 2009). When an alternating current passes through a metal wire, located in a magnetic field, a standing wave could occur (Kinchin, 2001). Here we extend this idea and propose a simple experimental equipment which can be easily assembled and used by the students to introduce them to the standing waves, at the same time demonstrating the interaction between electric currents and magnetic field and the resonance behavior. Instead of the more commonly used signal generator (Fang, 2007) we use a fixed frequency of the mains voltage and a magnet to excite the wave, which makes our set-up very cheap and easy to multiply. The proposed experiment is a good experimental task for undergraduate and high school students, which trains the students how to collect and process experimental data. It was given as an experimental problem to undergraduate students at the National Physics Olympiad of Bulgaria in 2008.

Equipment

The core of the set-up is a magnet placed under a stretched wire, through which an alternative current of 50 Hz flows. Different tension forces are applied to the wire using appropriate loads. The resonant condition for vibrations is achieved by changing the effective wire length using a slider.

The equipment, needed for the experiment, consists of a copper wire (suitable diameter 0.15-0.20 mm) attached to a rail, a 9V AC adaptor, 6 loads each of 29 g (fishing sinkers are suitable), a 50 cm ruler, a slider and a bar magnet. To the one end of the wire (which is grounded) a tension force is applied using loads, put in a plastic cup. A 120 Ohm resistor, connected in series with the wire is limiting the current. A suitable plastic or wooden block can be used as a slider to change the wire's effective length. The resonant condition is easily detected by observation - the amplitude at the antinodes reaches several millimeters. The sound from the vibrating string can be even heard by the experimenter. Photograph of the entire equipment is shown on figure 1.

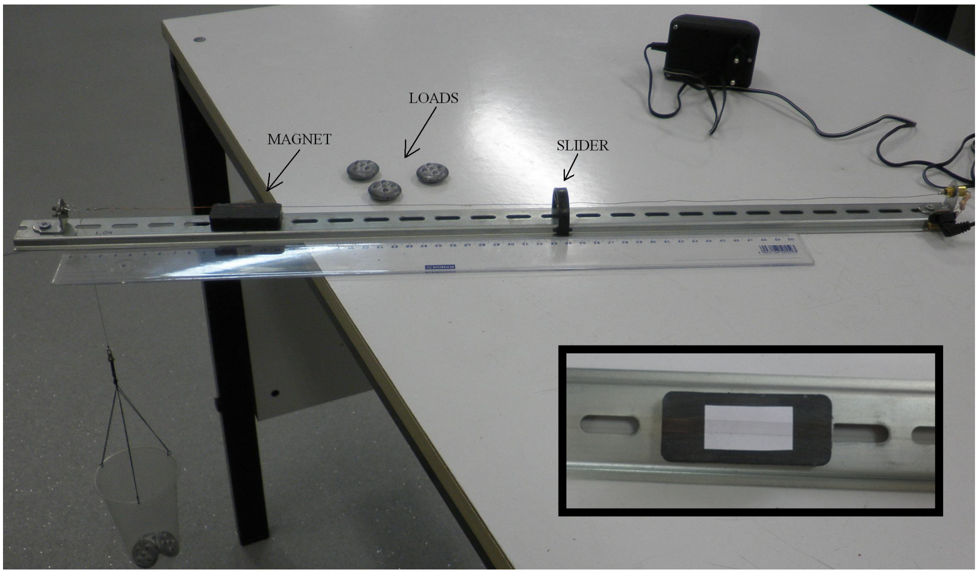

Figure 1. *Photograph of the entire set-up used for the experiments. The inset shows the wire amplitude at the resonance condition*

Brief Theory

Here we briefly explain the background knowledge required by the students for performing this experiment. The velocity u of a travelling wave in a stretched string is determined by the tension T and the linear mass density μ of the string

$$u = \sqrt{\frac{T}{\mu}} . \tag{1}$$

The tension force applied to the wire depends on the weight of the additional masses (m) loaded in the cup and it is

$$T = mg , \tag{2}$$

where g is the acceleration of gravity. The additional information that the students need are the acceleration of gravity ($g = 9.81\ m/s^2$) and the copper density ($\rho = 8.93 \times 10^3\ kg/m^3$).

Experimental Tasks

Students are given the following experimental tasks:

(1) Investigate experimentally the relationship between the wavelength of the transverse standing wave and the applied tension force.

(1.1) Determine the length of the transverse standing wave in the string at different tension forces.

(1.2) Record the data in a table.

(1.3) Describe how you carry out the measurements. Include a description of the magnet position in the different situations.

(1.4) Point out which are the most important sources of errors and how they influence the final results.

(2) Use convenient variable combinations to express your data via a straight line.

(2.1) Explain the influence of the plastic cup mass and the friction force on the straight line parameters.

(3) Determine the linear mass density of the wire.

(4) Determine the wire radius.

At every stage of the experiment the students are required to find the absolute and the relative uncertainty of the determined parameters.

Before starting with the measurements, it could be discussed with the students the role of the magnet in order to be able to put it in the correct position and the nature of the expected vibrations. They also have to take care when loading the masses in the cup not to pull off the wire.

Exemplary Results and Discussion

To solve the first experimental task (1.1 from the above section) the students should connect the wire length to the wavelength. When the wire length (L) is equal to an integer number (k) of half wavelengths ($\lambda/2$) a standing wave occurs

$$L = k\lambda/2\,, \tag{3}$$

which wavelength can be expressed from equation 3 as

$$\lambda = 2L/k\,. \tag{4}$$

Moving the slider along the rail the students find the resonant wire length, which satisfies condition (3) for the transverse standing wave. Loading different masses in the plastic cup, the students find the corresponding wavelength using equation (4) (task 1.3). Usually they measure the fundamental (k=1), though overtones can also be used. Exemplary experimental data are presented in table 1 (task 1.2).

Table 1. *Experimental data for the wavelength of the standing wave at different masses loaded*

Mass m (g)	Resonant wire length L (m)	Wavelength λ (m)
29	0.207	0.414
58	0.284	0.568
87	0.324	0.648
116	0.360	0.720
145	0.408	0.816
174	0.452	0.904

To improve the accuracy the students should repeat measurements several times at a given mass. The biggest uncertainties here are introduced by the wire resonant length, which the students usually determine with an absolute error $\Delta L = \pm 0.002\, m$ (task 1.4).

The next step is to present the collected data via a straight line (task 2). Knowing that the speed of the wave depends on its frequency ν and the wavelength λ as

$$u = \nu\lambda , \tag{5}$$

and combining equations 1, 2 and 5, for the mass of the added loads one obtains

$$m = \frac{\mu\lambda^2\nu^2}{g} . \tag{6}$$

The best way is to express the data as $m = m(\lambda^2)$ or, alternatively as $\lambda^2 = \lambda^2(m)$. On figure 2 the collected experimental data expressed as $m = m(\lambda^2)$ are presented. Linear regression analysis of these data gives

$$m = 231.31\lambda^2 - 10.89 . \tag{7}$$

It is obvious from equation 6 that the straight line must pass through the beginning of the coordinate system, but in a real experiment it is slightly shifted. The students must conform that this is due to the weight of the plastic cup and the friction at the wire bend, which are not taken into account in equation 6 (task 2.1). Both are equivalent to an additional mass, applied to the wire, and the equation 7 now takes the form

$$m + m_0 = 231.31\lambda^2 , \tag{8}$$

where $m_0 = 10.89\, g$ is the extra mass in this particular case. Usually the students obtain values between $4\, g$ and $20\, g$ for m_0.

From the slope of the linear fit of the data on figure 2 and equation 6 the linear mass density μ could be determined. In the particular case $\mu = 0.9 \pm 0.1\, g/m$ (task 3).

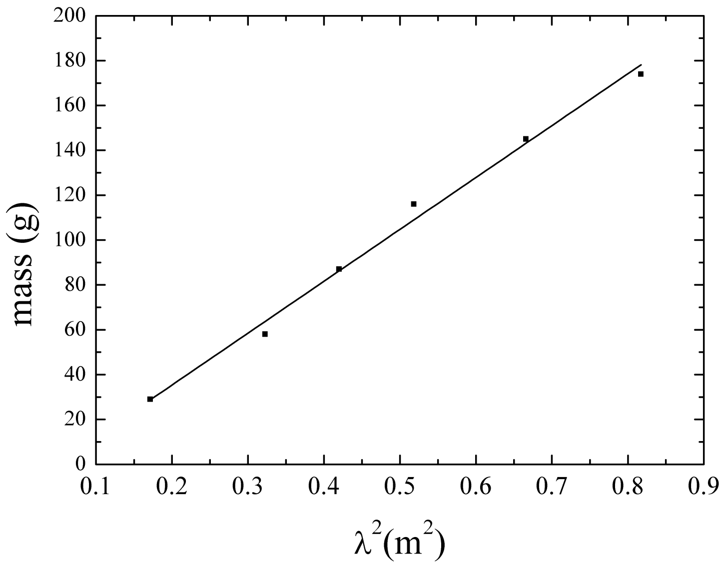

***Figure 2**. Experimental data expressed as the loaded mass versus the square of the wavelength of the standing wave*

For the last task (task 4), determination of the wire radius, the students have to use that

$$\mu = m_w / l\,, \tag{9}$$

where m_w is the wire mass and l is its full length. Assuming the wire is a long cylinder with a radius r and a density ρ, for the wire mass one obtains

$$m_w = \pi\rho l r^2\,. \tag{10}$$

Substituting equation 10 in 9 the wire radius can be expressed as

$$r = \sqrt{\frac{\mu}{\pi\rho}}\,. \tag{11}$$

Working carefully the students obtain for the wire radius $0.18\,mm$ with an uncertainty no greater than 5%.

Conclusion

The presented here experimental tasks use a simple and low cost equipment to demonstrate a standing wave in a string. The main advantage of the proposed approach to this well-known experiment is the usage of a fixed mains frequency and geometrical adjustment of the resonance, instead of a variable frequency. This makes unnecessary a frequency generator, leading to low cost of the equipment and giving a possibility to use multiple setups in a class.

The experimental setup is successfully used to determine the linear mass density and the radius of a metal wire and it is also suitable for a lecture demonstration of the standing waves, interaction between electric current and magnetic field and the resonance phenomena.

Acknowledgments

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References

Chen, D. (2009) Vibration frequency can be used to determine an unknown mass. *Physics Education,* 44(3), 232-234.

Fang, T. S. (2007) Analysis on non-resonance standing waves and vibration tracks of strings. *European Journal of Physics,* 28(4), 665-672.

Gluck, P. (2009) Plucked string on a shoestring budget. *The Physics Teacher,* 47(1), 13-17.

Kashy, E., Johnson, D. A., Mcintyre, J. & Wolfe, S. L. (1997) Transverse standing waves in a string with free ends. *American Journal of Physics,* 65(4), 310-313.

Kinchin (2001) Let's investigate: Standing waves on strings. *Physics Education,* 36(3), 255.